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METHODS OF DETERMINING HIP JOINT CENTRE: THEIR INFLUENCE ON THE 3-D KINEMATICS OF THE HIP AND KNEE DURING THE FENCING LUNGE

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ABSTRACT
Purpose. The lunge is a fundamental offensive fencing technique, common to all contemporary fencing styles. Therefore, when using 3-D kinematic analysis to quantify lower extremity rotations during the fencing lunge, it is important for researchers to correctly interpret this movement. Locating the centre of the hip is required to accurately quantify hip and knee joint rotations, with three non-invasive techniques using anatomical, functional and projection methods currently available for the estimation of hip joint centre. This study investigated the influence of these three techniques on hip and knee joint kinematics during the fencing lunge. **Methods.** Three-dimensional kinematics of the lunge were collected from 13 experienced epee fencers using an eight-camera motion capture system. The 3-D kinematics of the lunge were quantified using the three hip joint centre estimation techniques. Repeated measures ANOVAs were used to compare the discrete 3-D kinematic parameters, and intra-class correlations were employed to identify similarity across the 3-D kinematic waveforms from the three techniques. **Results.** The results indicate that whilst the kinematic waveforms were similar ($R^2 \geq 0.96$); significant differences in discrete parameters were also evident at both the hip and knee joint in the coronal and transverse planes. **Conclusions.** It appears based on these observations that different hip joint centre locations can significantly influence the resultant kinematic parameters and cannot be used interchangeably.

Key words: hip joint centre, kinematics, fencing, lunge

Introduction

A powerful fencing lunge is fundamental to successful performance, it being the most common attack with all three fencing weapons: the foil, epee and sabre. The lunge is an explosive movement that begins from an en-guard position, with the feet shoulder-width apart, where the back foot is 90 degrees to the forward-facing front foot. The fencer then straightens their sword arm and pushes off from their back leg while lifting up and kicking out their front leg for the lunge. To score, a fencer lunges from the en-guard position quickly closing the distance to the opponent and touches the opponent with his/her weapon. Unlike the forward lunge common in many other sports, the fencing lunge maintains a perpendicular orientation of the feet, where the sole of the non-leading foot remains planted on the ground and the non-leading leg is forcefully and almost completely extended.

When using 3-D kinematic analysis to quantify lower extremity rotations during the fencing lunge, it is important for researchers to correctly interpret this movement. In recent years, efforts have been made to improve 3-D kinematic techniques during motion analysis in order to accurately model and track body segments. Movement artefact has been reduced via the utilization of the calibrated anatomical systems technique (CAST), using tracking clusters placed on body segments to create technical coordinate systems [1]. However, modelling of the thigh segment remains difficult [2], particularly at its proximal insertion with the pelvis, as there are number of techniques that are available for the location of the hip joint centre.

Locating the centre of the hip is required to calculate hip joint rotations and moments in 3-D kinematic analysis [3–5]. The hip joint centre is an important identifying landmark in human movement analysis as it allows for the determination of the anatomical reference frame of the femur [1]. A number of techniques currently exist that include anatomical [6], functional [7, 8] and projection [9] methods, all of which may influence the resultant hip and knee joint profiles [5]. Although the validity of each method has been reported to justify their utilization, there is currently a lack of information regarding the influence of the three available hip joint centre location techniques on 3-D kinematic parameters during fencing movements and the interchangeable use of each technique [10]. Furthermore, whilst investigations have been conducted whereby the accuracy of each technique in determining the anatomical position of the hip joint centre was examined using radiographic imaging, there is a paucity of information regarding the influence of the different techniques upon the resultant kinematic waveforms and discrete variables.

Therefore, the aim of the current investigation was to compare the 3-D kinematics of the fencing lunge

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quantified using three different (anatomical, projection and functional) hip joint centre estimation techniques via both discrete variable and waveforms analyses.

Material and methods

Thirteen participants including eight males and five females volunteered to take part in this investigation. All were competitive epee fencers with a minimum of five years' experience. Participants were free of injury at the time of data collection and provided written informed consent in accordance with the Declaration of Helsinki, with the procedure utilized for this investigation approved by the ethical committee at the University of Central Lancashire. The mean characteristics of the participants were: age 27.61 ± 4.50 years, height 172.32 ± 7.60 cm and body mass 71.29 ± 8.49 kg. A statistical power analysis was conducted using Hopkins' method to reduce the probability of type II error and define the minimum number of participants needed for this examination. It was found that the sample size was sufficient to provide more than 80% statistical power.

The fencers completed a suitable warm-up and were allowed time to familiarize themselves with the experimental protocol prior to the commencement of data collection. They were then required to complete 10 trials hitting a dummy with their weapon whilst returning to a starting point (pre-determined by each participant prior to the commencement of data capture) following each trial to control lunge distance. The participants began with their right (lead) foot on a force platform (Kistler Instruments Ltd., England), which was embedded in the floor (Altrosports 6mm, Altro Ltd., England) of the biomechanics laboratory where the study was performed.

Kinematic data were captured at 200 Hz via an eight-camera motion analysis system (Qualisys Medical AB, Sweden). Calibration of the required capture volume was performed before each data collection session. Only calibrations which produced average residuals of less than 0.85 mm for each camera for a 750.5 mm wand length and point residuals above 4000 in all cameras were accepted prior to data collection.

The marker set used for the study was based on the calibrated anatomical systems technique (CAST) [1]. In order to define the lead leg's foot, shank and thigh, retro-reflective markers were attached unilaterally to the calcaneus, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral epicondyle of the femur and greater trochanter. To define the pelvis, additional retro-reflective markers were placed on the anterior (ASIS) and posterior (PSIS) superior iliac spines. All markers were positioned by the lead author. Rigid tracking clusters were positioned on the shank and thigh. Each rigid cluster comprised of four 19 mm diameter spherical reflective markers mounted to a thin sheath of light-weight carbon fibre with length-to-width ratios in accordance with Cappozzo et al. [11]. A static trial was conducted with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters, following which the non-technical markers (i.e. medial and lateral malleoli, medial and lateral epicondyle of the femur) were removed.

The anatomical technique that was used in the present study was based on the recommendations of Bell et al. [6] via the inter-ASIS breadth. This method places the hip joint centre 14% medial, 22% posterior and 30% distal from the ipsilateral (right) ASIS (Fig. 1).

The projection technique was also based on previously established recommendations [9], where this method estimated HJC as a three-dimensional point, located at one-quarter of the distance along a line from the ipsolateral (right) to the contralateral (left) greater trochanter markers during the static trials (Fig. 1).

To define the functional HJC, participants performed five sequential flexion-extension and abduction-adduction movements of the right hip at a self-selected velocity followed by a cycle of full hip circumduction [8]. Flexion-extension and abduction-adduction ranges of movement were in the order of 45° and 40°, respectively.

Trials were processed by Qualisys Track Manager in order to identify the anatomical and tracking markers

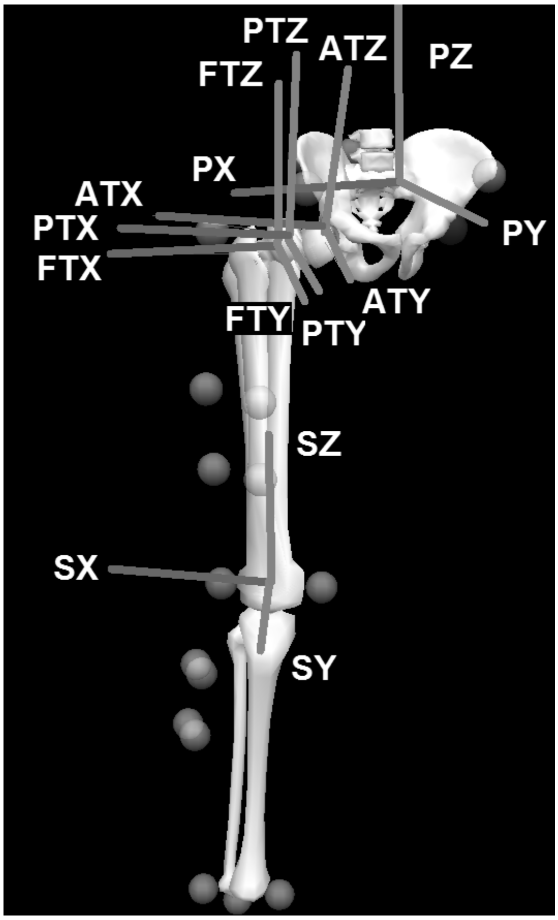

Figure 1. Pelvic, thigh, tibial and foot segments, with segment co-ordinate system axes (P_{XYZ} – pelvis, S_{XYZ} – shank; AT_{XYZ} – anatomical thigh, PT_{XYZ} – projection thigh, FT_{XYZ}– functional thigh)

and then exported as C3D files. Kinematic parameters were quantified using Visual 3-D (C-Motion Inc., USA) after marker data were smoothed using a low-pass Butterworth 4th order zero-lag filter at a cut-off frequency of 12Hz. This frequency was selected as being the frequency at which 95% of the signal power was contained below. Three-dimensional kinematics of the hip and knee were calculated using an XYZ cardan sequence of rotations (where X was flexion-extension, Y was abduction-adduction and Z was internal-external rotation) [12]. All data were normalized to 100% of the lunge movement, with the processed trials then averaged. The three-dimensional kinematic measures from the hip and knee that were extracted for statistical analysis were: 1) angle at initiation of movement, 2) angle at completion of lunge, 3) range of motion from initiation to completion of the lunge, 4) peak angle, 5) relative range of motion from initiation to peak angle 6) angular velocity at initiation, 7) angular velocity at completion of lunge, 8) peak angular velocity, 9) angular acceleration at initiation, 10) angular velocity at completion of lunge and 11) peak angular acceleration.

Descriptive statistics including means and standard deviations of the 3-D kinetic and kinematic parameters were calculated for each hip joint centre prediction technique. Differences between the parameters were examined using repeated measures ANOVA with significance accepted at the $p \leq 0.05$ level. Appropriate post-hoc analyses were conducted using a Bonferroni correction to control for type I error. Effect sizes were calculated using η^2. Cohen's suggestion on effect sizes was adopted (small $\eta^2 < 0.01$; medium ≥ 0.06 and large ≥ 0.13). If the sphericity assumption was violated then the degrees of freedom were adjusted using the Greenhouse-Geisser correction. In addition, intra-class correlations were utilized to compare between the sagittal, coronal, and transverse plane waveforms using the three different techniques. The Shapiro-Wilk statistic for each condition was used to confirm that data were normally distributed. All statistical procedures were conducted using SPSS 19.0 statistical software (SPSS Inc., USA).

Results

Figures 2–4 present the mean 3-D angular kinematics of the hip and knee joint during the lunge. Tables 1–6 present the 3-D kinematic parameters from the hip and knee observed as a function of the hip joint centre esti-

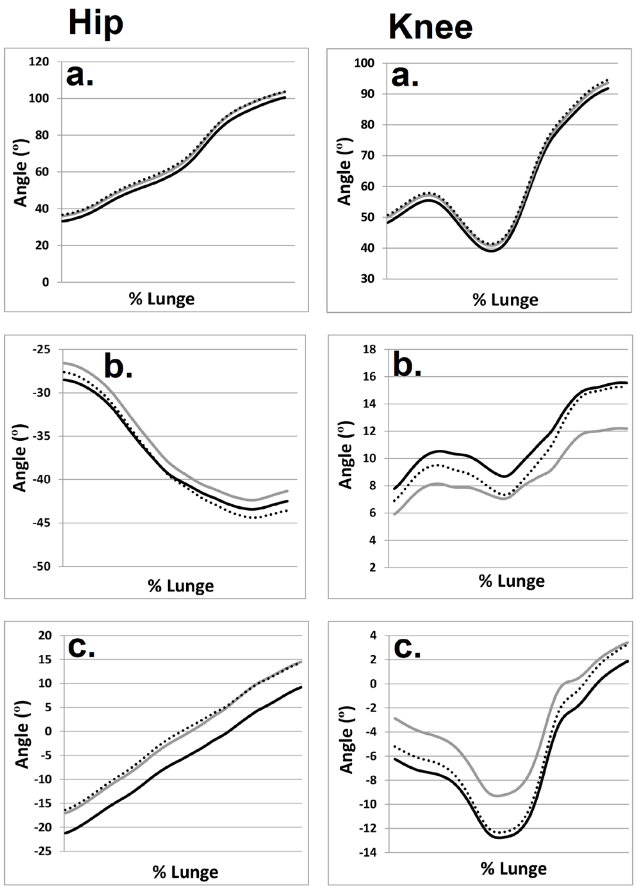

Figure 2. Hip and knee kinematics in the (a.) sagittal, (b.) coronal and (c.) transverse planes as a function of hip joint centre location (black line – anatomical technique, grey line – functional technique, dotted line – projection technique)

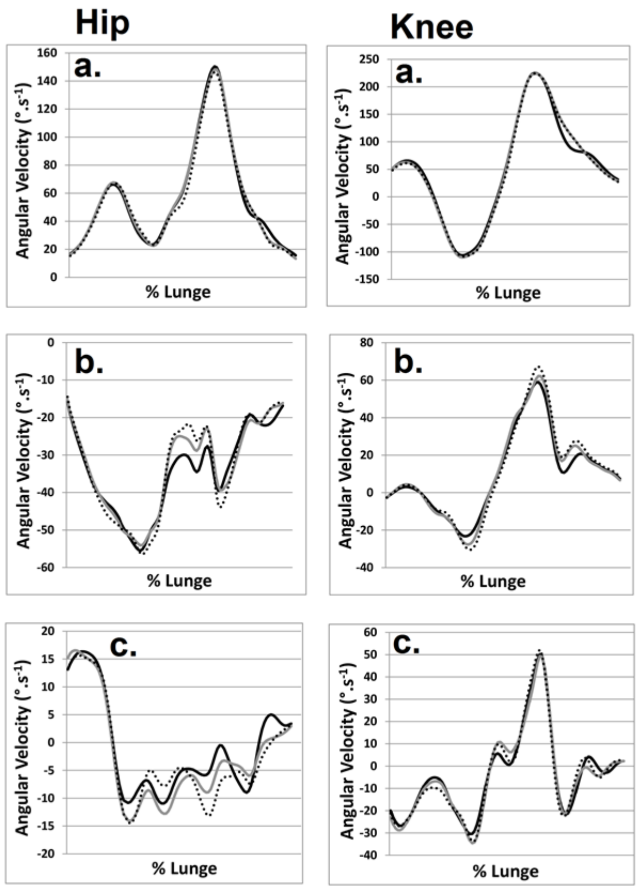

Figure 3. Hip and knee joint velocities in the (a.) sagittal, (b.) coronal and (c.) transverse planes as a function of hip joint centre location (black line – anatomical technique, grey line – functional technique, dotted line – projection technique)

Table 1. Hip joint kinematics (means and standard deviations) as a function of hip joint centre technique

Hip	Anatomical	Projection	Functional	
	Mean ± SD	Mean ± SD	Mean ± SD	
X (+ flexion/– extension)				
Angle at Initiation (°)	33.19 ± 12.35	35.64 ± 11.58	36.60 ± 11.42	
Angle at Completion (°)	101.89 ± 13.98	104.38 ± 12.57	104.61 ± 13.59	
Range of Motion (°)	68.70 ± 18.10	68.75 ± 18.33	68.01 ± 15.61	
Relative Range of Motion (°)	68.80 ± 18.13	68.84 ± 18.35	68.12 ± 15.64	
Peak Flexion (°)	101.99 ± 14.04	104.48 ± 12.59	104.71 ± 13.64	
Y (+ adduction/– abduction)				
Angle at Initiation (°)	–27.56 ± 7.32	–26.50 ± 7.82	–28.03 ± 8.49	
Angle at Completion (°)	–42.86 ± 11.43	–40.81 ± 10.61	–41.46 ± 11.22	
Range of Motion (°)	15.30 ± 12.24	14.51 ± 10.84	14.07 ± 12.07	
Relative Range of Motion (°)	21.07 ± 9.78	20.09 ± 9.89	19.43 ± 10.08	
Peak Abduction (°)	–48.63 ± 9.96	46.59 ± 9.66	–47.47 ± 8.76	
Z (+ internal/– external)				
Angle at Initiation (°)	–20.96 ± 13.19 ¥†	–17.30 ± 12.11	–16.51 ± 9.96	**
Angle at Completion (°)	10.10 ± 15.36 ¥	14.70 ± 14.65	14.58 ± 14.30	*
Range of Motion (°)	31.06 ± 18.38	32.01 ± 18.59	21.16 ± 16.77	
Relative Range of Motion (°)	33.48 ± 16.56	34.25 ± 17.07	33.72 ± 14.69	
Peak Internal rotation (°)	12.52 ± 15.35 ¥	16.95 ± 14.47	17.21 ± 13.27	*

* – significant at $p \le 0.05$; ** – significant at $p \le 0.01$; ¥ – significantly different from the functional technique;
† – significantly different from the projection technique

Table 2. Knee joint kinematics (means and standard deviations) as a function of hip joint centre projection technique

Knee	Anatomical	Projection	Functional	
	Mean ± SD	Mean ± SD	Mean ± SD	
X (+ flexion/– extension)				
Angle at Initiation (°)	48.57 ± 9.57	50.08 ± 10.61	50.83 ± 10.37	
Angle at Completion (°)	93.87 ± 8.83	94.87 ± 8.75	95.85 ± 8.43	
Range of Motion (°)	44.76 ± 14.15	44.79 ± 14.33	45.01 ± 13.97	
Relative Range of Motion (°)	21.88 ± 17.19	21.75 ± 17.08	21.94 ± 17.18	
Peak Flexion (°)	26.69 ± 12.71	28.33 ± 14.25	28.89 ± 15.11	
Y (+ adduction/– abduction)				
Angle at Initiation (°)	5.93 ± 6.99	6.78 ± 7.21	7.36 ± 8.01	
Angle at Completion (°)	11.99 ± 9.50 ¥	14.69 ± 10.77	15.06 ± 10.50	**
Range of Motion (°)	6.22 ± 3.93	7.96 ± 5.22	7.71 ± 4.77	
Relative Range of Motion (°)	3.97 ± 3.52	4.76 ± 3.96	4.07 ± 4.26	
Peak Adduction (°)	1.96 ± 7.45	2.02 ± 7.30	3.30 ± 8.23	
Z (+ internal/– external)				
Angle at Initiation (°)	–3.81 ± 8.98 †	–6.85 ± 9.93	–6.14 ± 11.06	*
Angle at Completion (°)	3.00 ± 10.27	1.53 ± 10.24	2.48 ± 12.46	
Range of Motion (°)	8.56 ± 3.27	10.06 ± 4.62	10.13 ± 4.70	
Relative Range of Motion (°)	12.30 ± 7.04	12.34 ± 6.88	12.95 ± 7.14	
Peak External rotation (°)	–16.10 ± 11.87 †	–19.18 ± 11.97	–19.09 ± 12.08	*

* – significant at $p \le 0.05$; ** – significant at $p \le 0.01$; ¥ – significantly different from the functional technique;
† – significantly different from the projection technique

mation technique. The results indicated that the kinematic waveforms were similar but significant differences in discrete parameters were also evident.

Hip joint angles

In the transverse plane, a significant main effect $F(2, 24) = 6.53$, $p \leq 0.01$, $\eta^2 = 0.35$ was observed for the magnitude of rotation at the commencement of the lunge movement. Post-hoc analysis revealed that the anatomical technique was associated with significantly ($p = 0.02$) more external rotation than the functional method. A significant main effect $F(2, 24) = 4.15$, $p \leq 0.01$, $\eta^2 = 0.26$ was also observed for the magnitude of rotation at the completion of the movement. Post-hoc analysis revealed that the anatomical technique was associated with significantly ($p = 0.04$) less external rotation than the functional method. Finally, a significant main effect $F(2, 24) = 4.50$, $p \leq 0.05$, $\eta^2 = 0.27$ was observed for the magnitude of peak transverse plane rotation. Post-hoc analysis revealed that the anatomical technique was associated with significantly ($p = 0.04$) less external rotation than the functional method.

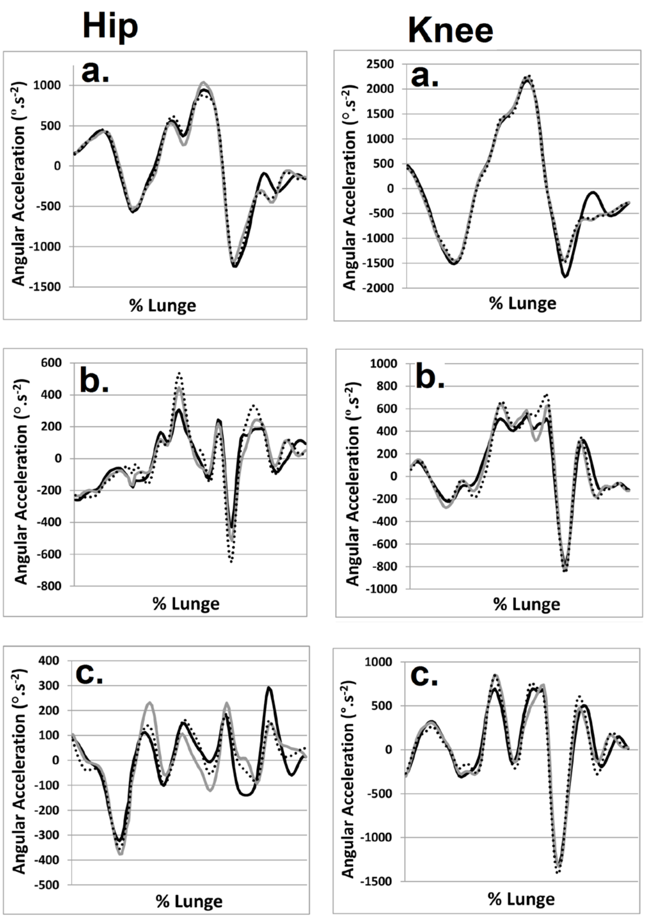

Figure 4. Hip and knee joint accelerations in the (a.) sagittal, (b.) coronal and (c.) transverse planes as a function of hip joint centre location (black line – anatomical technique, grey line – functional technique, dotted line – projection technique)

Comparisons between hip waveforms using the three different methods revealed strong correlations in all three planes of rotation: sagittal ($R^2 = 0.99$), coronal ($R^2 = 0.97$) and transverse ($R^2 = 0.96$).

Knee joint angles

In the coronal plane, a significant main effect $F(1.13, 13.58) = 5.95$, $p \leq 0.01$, $\eta^2 = 0.33$ was observed for the magnitude of rotation at the completion of the lunge movement. Post-hoc analysis revealed that the functional method was associated with significantly ($p = 0.04$) more adduction in comparison with the anatomical technique. In the transverse plane, a significant main effect $F(2, 24) = 3.67$, $p \leq 0.05$, $\eta^2 = 0.26$ was also observed for the magnitude of rotation at the commencement of the lunge movement. Post-hoc analysis revealed that the projection method was associated with significantly ($p = 0.04$) more external rotation than the anatomical technique. Finally, a significant main effect $F(2, 24) = 4.88$, $p \leq 0.05$, $\eta^2 = 0.20$ was observed for the magnitude of peak transverse plane rotation. Post-hoc analysis revealed that the projection method was associated with significantly ($p = 0.04$) more external rotation than the anatomical technique.

Comparisons between knee waveforms using the three different methods revealed strong correlations in all three planes of rotation: sagittal ($R^2 = 0.99$), coronal ($R^2 = 0.96$) and transverse ($R^2 = 0.94$).

Hip joint velocities

No significant ($p \geq 0.05$) main effects were observed for any of the hip joint angular velocity parameters observed as a function of hip joint centre location technique. Comparisons between hip waveforms using the three different methods revealed strong correlations in all three planes of rotation: sagittal ($R^2 = 0.99$), coronal ($R^2 = 0.98$) and transverse ($R^2 = 0.95$).

Hip joint accelerations

No significant ($p \geq 0.05$) main effects were observed for any of the hip joint angular acceleration parameters observed as a function of hip joint centre location technique. Comparisons between hip waveforms using the three different methods revealed strong correlations in all three planes of rotation: sagittal ($R^2 = 0.99$), coronal ($R^2 = 0.97$) and transverse ($R^2 = 0.95$).

Knee joint accelerations

No significant ($p \geq 0.05$) main effects were observed for any of the knee joint angular acceleration parameters observed as a function of hip joint centre location tech-

Table 3. Hip joint velocities (means and standard deviations) as a function of hip joint centre technique

Hip	Anatomical	Projection	Functional
	Mean ± SD	Mean ± SD	Mean ± SD
X (+ flexion/– extension)			
Velocity at Initiation (° · s–1)	19.65 ± 33.31	18.45 ± 31.01	19.06 ± 30.12
Velocity at Completion ($° \cdot s^{-1}$)	18.88 ± 27.09	19.81 ± 26.37	19.12 ± 26.06
Peak Velocity ($° \cdot s^{-1}$)	155.61 ± 41.22	152.33 ± 42.39	153.71 ± 41.31
Y (+ adduction/– abduction)			
Velocity at Initiation ($° \cdot s^{-1}$)	–14.31 ± 16.66	–14.66 ± 15.8	–15.10 ± 16.10
Velocity at Completion ($° \cdot s^{-1}$)	–16.20 ± 15.52	–15.75 ± 15.20	–15.70 ± 16.08
Peak Velocity ($° \cdot s^{-1}$)	–55.60 ± 20.19	–53.78 ± 22.30	–56.19 ± 21.61
Z (+ internal/– external)			
Velocity at Initiation ($° \cdot s^{-1}$)	13.50 ± 10.12	15.37 ± 11.16	16.39 ± 10.65
Velocity at Completion ($° \cdot s^{-1}$)	3.58 ± 9.87	3.51 ± 8.96	3.59 ± 7.99
Peak Velocity ($° \cdot s^{-1}$)	–10.88 ± 13.61	–14.31 ± 14.20	–14.60 ± 13.88

Table 4. Knee joint velocities (means and standard deviations) as a function of hip joint centre technique

Knee	Anatomical	Projection	Functional
	Mean ± SD	Mean ± SD	Mean ± SD
X (+ flexion/– extension)			
Velocity at Initiation ($° \cdot s^{-1}$)	51.30 ± 20.11	50.39 ± 18.89	50.82 ± 19.38
Velocity at Completion ($° \cdot s^{-1}$)	38.60 ± 16.69	38.03 ± 15.80	37.63 ± 16.98
Peak Velocity ($° \cdot s^{-1}$)	228.38 ± 20.12	230.30 ± 19.62	227.39 ± 21.22
Y (+ adduction/– abduction)			
Velocity at Initiation ($° \cdot s^{-1}$)	–3.66 ± 12.37	–2.69 ± 13.30	–3.11 ± 12.01
Velocity at Completion ($° \cdot s^{-1}$)	8.38 ± 11.90	7.89 ± 10.89	8.02 ± 11.09
Peak Velocity ($° \cdot s^{-1}$)	57.39 ± 18.89	62.30 ± 19.21	67.91 ± 20.01
Z (+ internal/– external)			
Velocity at Initiation ($° \cdot s^{-1}$)	–20.16 ± 13.39	–23.68 ± 14.00	–24.61 ± 15.38
Velocity at Completion ($° \cdot s^{-1}$)	2.31 ± 10.16	1.60 ± 11.22	1.78 ± 10.36
Peak Velocity ($° \cdot s^{-1}$)	50.60 ± 19.39	51.09 ± 19.69	51.96 ± 20.31

nique. Comparisons between hip waveforms using the three different methods revealed strong correlations in all three planes of rotation: sagittal ($R^2 = 0.99$), coronal ($R^2 = 0.98$) and transverse ($R^2 = 0.95$).

Discussion

The aim of the current investigation was to compare the 3-D kinematics of the hip and knee during the fencing lunge using three different hip joint centre location techniques. This study represents the first to examine the differences between hip joint centre estimation techniques when quantifying lower extremity kinematics during the fencing lunge.

In the sagittal plane, no differences were observed between discrete parameters for the hip or knee joint between any of the three hip joint centre locations techniques (Tab. 1–6). In addition to this, the highest intra-class ($R^2 \geq 0.99$) correlations were observed for the sagittal plane waveforms indicating a high level of similarity across all techniques in the sagittal plane.

In the coronal and transverse planes, although the intra-class correlations showed a good level of agreement between waveforms ($R^2 \geq 0.95$), significant differences between the three hip joint centre estimation techniques were observed for both the hip and knee angles. This suggests that different techniques for the determination of hip joint centre may affect overall discrete kinematic parameters. It should be noted that the anatomical technique was typically different from the functional and projection methods in the transverse plane. This concurs with the findings of Eng and Winter [13] and Bowsher and Vaughan [14], who both noted that transverse plane hip joint kinematics were

Table 5. Hip joint accelerations (means and standard deviations) as a function of hip joint centre technique

Hip	Anatomical	Projection	Functional
	Mean ± SD	Mean ± SD	Mean ± SD
X (+ flexion/– extension)			
Acceleration at Initiation (° · s^{-2})	185.33 ± 25.54	180.69 ± 23.60	186.69 ± 24.50
Acceleration at Completion (° · s^{-2})	–170.39 ± 31.62	–173.41 ± 33.90	–171.26 ± 30.62
Peak Acceleration (° · s^{-2})	929.81 ± 39.31	1030.53 ± 42.31	818.38 ± 39.89
Y (+ adduction/– abduction)			
Acceleration at Initiation (° · s^{-2})	–251.81 ± 30.31	–230.60 ± 31.49	–226.11 ± 30.89
Acceleration at Completion (° · s^{-2})	121.39 ± 26.67	153.12 ± 28.89	141.92 ± 30.13
Peak Acceleration (° · s^{-2})	295.61 ± 41.69	426.39 ± 43.81	566.91 ± 40.20
Z (+ internal/– external)			
Acceleration at Initiation (° · s^{-2})	94.22 ± 36.96	106.12 ± 31.38	100.50 ± 32.09
Acceleration at Completion (° · s^{-2})	20.13 ± 40.03	22.38 ± 37.68	46.68 ± 35.81
Peak Acceleration (° · s^{-2})	–313.31 ± 51.69	–385.99 ± 50.21	–366.33 ± 48.62

Table 6. Knee joint accelerations (means and standard deviations) as a function of hip joint centre technique

Knee	Anatomical	Projection	Functional
	Mean ± SD	Mean ± SD	Mean ± SD
X (+ flexion/– extension)			
Acceleration at Initiation (° · s^{-2})	486.21 ± 26.12	469.09 ± 30.11	473.21 ± 28.29
Acceleration at Completion (° · s^{-2})	–311.31 ± 30.11	–299.91 ± 29.07	–307.68 ± 30.67
Peak Acceleration (° · s^{-2})	2195.65 ± 126.16	2213.39 ± 120.90	2225.51 ± 122.38
Y (+ adduction/– abduction)			
Acceleration at Initiation (° · s^{-2})	86.16 ± 51.21	81.29 ± 48.96	73.71 ± 47.77
Acceleration at Completion (° · s^{-2})	–109.21 ± 43.23	–112.32 ± 41.16	–111.31 ± 40.17
Peak Acceleration (° · s^{-2})	–821.31 ± 106.69	–819.59 ± 101.37	–826.69 ± 107.91
Z (+ internal/– external)			
Acceleration at Initiation (° · s^{-2})	–261.31 ± 49.61	–266.38 ± 44.82	–263.10 ± 45.90
Acceleration at Completion (° · s^{-2})	2.90 ± 31.21	3.86 ± 36.19	2.12 ± 31.91
Peak Acceleration (° · s^{-2})	–1229.19 ± 111.28	–1261.31 ± 108.20	–1330.91 ± 119.61

sensitive to anatomical frame alterations. It is likely that this observation is a reflection of the more medial position of the HJC in the anatomical technique compared with the functional and projection configurations. Given that the co-ordinate systems of the segments are based on the positions of the proximal and distal joint centres, the pose of the thigh segment is altered. This caused the thigh segment to be more externally rotated leading to increases in hip external rotation and knee internal rotation in the anatomical technique.

This observation concurs with the findings of Sinclair et al. [10], who also observed statistical differences when examining 3-D kinematics of the hip and knee during running when using three different hip joint centre location techniques. However, the extent of the differences between hip joint centre location techniques can be conceptualized through inspection of the effect sizes, which are considered small to moderate based on Cohen's recommendations [15]. This indicates that whilst there are significant differences between techniques, the overall influence of the hip joint centre location on 3-D kinematic parameters is generally low.

Nonetheless, the observations from the current investigation may have potential clinical significance particularly in movements such as the lunge where high loading of the lower extremities occurs [16] in conjunction with relatively large coronal transverse plane motions of the hip and knee joints. Mizuno et al. [17], Horton and Hall [18] and Koga et al., [19] documented that increases in non-sagittal rotations at the hip and knee, which were shown to be significantly greater in the functional and projected techniques, are associated with the aetiology of injury to the lower extremities. Therefore it appears that researchers should carefully consider their choice of hip joint centre location technique when quantifying non-sagittal rotations and selecting clinical normative data, as it may affect the interpretation of their data.

It should be noted that the hip joint centre location has little influence on first and second derivative angular parameters. This leads to the conclusion that alterations in hip joint centre location can have a significant influence on angular displacement information, there does not seem to been any effects when quantifying angular kinematics for derived angular velocity and acceleration information. However, whilst this study considered angular displacement and derivative information, joint moments using inverse dynamics are also important in describing musculoskeletal movements [20]. Future work may wish to examine the influence of the hip joint centre on hip and knee joint moments during the fencing lunge.

That no radiographic measures were included in the current investigation may serve as a potential limitation, as the accuracy in determining the true location of the hip joint centre could not be documented. However, this is an invasive technique that is rarely used due to institutional ethical concerns and that radio-graphical planar films can be susceptible to parallax errors and poor control of participant positioning [21]. Furthermore, whilst this study provided information regarding the differences in discrete parameters and kinematic waveforms, the inter/intra-examiner reliability in defining the hip joint centre was not examined in terms of these parameters. This is a factor that future work may wish to address before an optimal estimation technique can be recommended.

Conclusions

In summary, whilst it is beyond the scope of this report to determine an optimal technique for the estimation of the hip joint centre, it does provide important information in that the different techniques yielded statistically significantly different discrete parameters when quantifying rotations outside the sagittal plane. Therefore, it appears that they may not be able to be used as interchangeably as has previously been commonplace in the literature on the subject and that cross-study comparison of hip and knee joint kinematics during the fencing lunge should be made with caution.

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